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by; P.A.Gordienko

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DREIF L'DOV V TSENTRAL'NOI CHASTI SEVERNOGO LEDOVITOGO OKEANA
(ICE DRIFT IN THE CENTRAL PART OF THE ARCTIC OCEAN)

BY

P. A. GORDIENKO

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ABSTRACT

Ice displacements in the Arctic Ocean are analyzed with respect to direction and speed in various sectors of the ocean, taking into consideration the essential components of ice drift, such as wind drift, currents, their fluctuations and shifts, atmospheric conditions, and other factors. The analysis is based on observational data concerning the drift of the Soviet North Pole stations, notably NP-3, NP-4 and NP-5 in 1954-1955. In conclusion, the prospects and accuracy in forecasting the ice movements and conditions that affect navigation on the Northern Sea Route are evaluated.

Translator

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ICE DRIFT IN THE CENTRAL PART OF THE ARCTIC OCEAN

One of the basic objectives of the drifting stations North Pole (referred to as SP; N.P. in English. Translator) was the elucidation of laws which determine the ice drift in the Arctic Ocean. The investigations are necessary for the improvement of methods in ice forecasting and also for the clarification of causes that are manifest almost every year in the Northern Sea Route, now worsening, now improving the conditions for navigation.

The northern sea route crosses the margins of the seas of which we possess sufficient information concerning the distribution of ice, wind and of air pressure. Less materials have been collected with respect to the central part of the Arctic Ocean. This fact limits considerably the possibilities of analyzing the displacement of great ice fields.

Besides, the investigations carried out by the Soviet scientists showed that in high latitudes the drift of ice affects substantially the formation of the basic ocean ice masses whose southern branches cross the Northern Sea Route. The masses usually appear to be the main ice obstacles for navigation.

With the extension of observations covering wide geographical areas, it becomes clear that in certain years the over-all pattern of ice drift (Fig. 1.) can be subject to great changes and deviations. The investigation of causes for these irregularities and deviations from the set pattern in the work of such a gigantic planetary machine as is the interaction between the oceans of the water and the air is of great interest. At the same time, it could be said that even the greatest deviations occurring in the circulation of water masses and ice cannot change the over-all pattern of ice drift.

The investigations of the latest years clarified that the ice drift in the regions of the Arctic Ocean adjacent to the Beaufort Sea, the Chukchi Sea and the East Siberian Sea are subject to the action of local atmospheric circulation to a greater extent than in other areas. In the areas adjacent to the Greenland Sea, the role of the wind drift component diminishes, whereas the role of the other drift component - i.e. the outgoing compensatory surface current, which brings the ice from the Arctic Ocean into the Greenland Sea through the strait lying between Greenland and Spitzbergen - increases.¹

/6

One of the important conclusions arrived at from the investigations (N. N. Zubov, D. B. Karelin, M. M. Somov, V. Kh. Buinitskii, P. A. Gordienko et al.) was the division of the Soviet Arctic seas into two major groups by the character of drift - namely, the seas of outgoing ice and the seas of incoming ice. To the first group belong the Kara and Laptev seas; to the second, the East Siberian Sea and, to a certain degree, the Chukchi Sea.

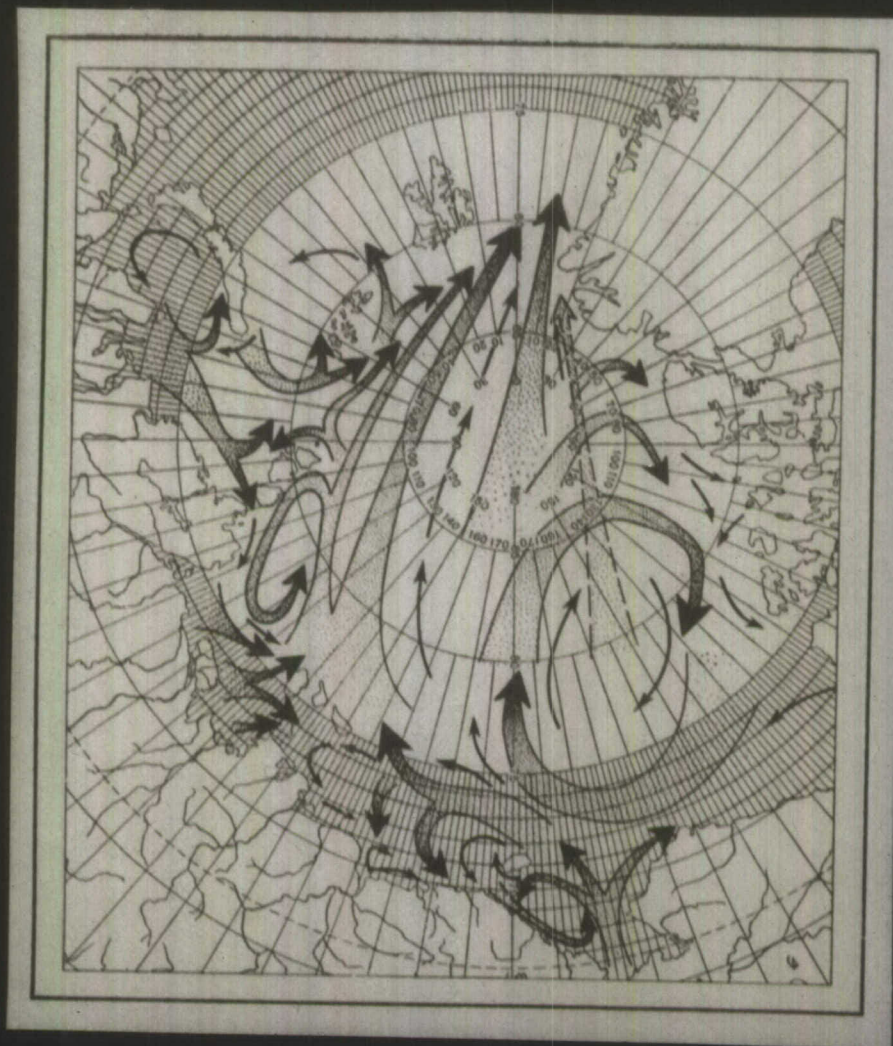
The concepts on the significance of pulsations in the transport of ice from the Arctic Ocean into the Greenland Sea have changed substantially during the last years.

The investigations accomplished by the scientists of the Arctic Institute convincingly substantiated the possibility of applying the so-called "Zubov laws" with respect to ice drift in computing the wind component of ice drift.

By the use of the exclusion method, provided sufficient observation material on ice drift is at hand, it is possible to obtain data on the speed and direction of the so-called "constant currents" in open areas of oceans and Arctic seas.

¹In 1938 N. N. Zubov rightly called it the Papanintsev Strait, and we will use the name.

Figure 1. The diagram of the predominant direction of basic ice displacements in the Arctic Ocean.



The use of "Zubov's law" in analyzing the drift of the Fram, G. Sedov and the stations NP permitted the elucidation of the major causes for the displacement of ice along the arc of the great circle in the European sector of the Arctic Ocean and the anti- /7 cyclonic circulation in the Canadian-American sector of the ocean. One of the major causes is the predominant distribution of air pressure and, consequently, the prevailing winds over the Arctic Ocean and the North Atlantic. If the basic relief of the atmosphere lying directly over the Arctic Ocean forms the wind component of drift, over the North Atlantic it determines the magnitude of pulsations in the stream of compensatory transport of water and ice from the Arctic Ocean into the Greenland Sea.

The position of the polar anticyclonic high pressure area also explains satisfactorily the circular motion of ice in the Canadian-American sector of the Arctic Ocean.

It should be remembered that, for the first time, the hypothesis on the circular drift of ice in the Canadian-American sector was mentioned in the scientific review of the team of Russian Polar Expedition on the schooner Zaria published in 1907. It is noteworthy that, already at that time, the hypothesis was based on the influence exerted by the winter anticyclon of the area.

The regularity of circular drift in the sector of ocean was theoretically formulated by N. N. Lubov (1938) and, later, confirmed by observations carried out by the high latitude expeditions under the guidance of V. F. Burkhanov and by the drift of station NP-2.

In this article, the writer has attempted to describe more precisely the general pattern of ice drift in the Arctic Ocean on the

basis of analysis with respect to the displacement of stations NP in the spring-summer period in 1954-1955. Such analysis is of great practical interest; specifically, the analysis permitted the elucidation of causes for the sharp increase in iciness and for the deterioration of navigational conditions in the Chukchi and East Siberian seas, which occurred in 1954 and 1955.

In those years, the heavy polar ice, retreating in the spring northward with a speed nearing the mean, unexpectedly changed the direction of drift in July-August, turning southward and blocking the Chukotka coast.

In addition to the materials of stations NP in 1954-1955, the writer has used in this study hydrometeorological data obtained from the network of polar stations, the weather bureau, and aerial ice reconnaissance of the main Northern Sea Route.

The Drift of Station NP in 1954-1955 in the Spring-Summer Period

The general movement pattern of stations NP-3, NP-4 and NP-5 in the period April-September in 1954-1955 is shown in Figure 2.

The plotting of drift chart is based on the coordinates as they were at the beginning of each ten-day period (dekada). Ten-day periods were chosen for the purpose of depicting sufficiently perceivable changes of ice drift as regards the geographic perception against the background of the vast expanse of the Arctic Ocean. The initial coordinates are shown in Table 1.

The directions of ten-day and monthly drift vectors are orientated with respect to the 180°-meridian, which is more convenient for comparisons because the meridian is the mean for the arc of the great circle along which the displacement of stations NP occurred

and along which the ice is transported from polar regions to the Greenland Sea (Figure 1.).

It should be noted that, in studying the direction of ice drift for long time periods, frequently the information on the so-called "general" direction of ice movement does not reflect the essence of drift. Thus, for instance, in May-September, 1954, the "general" direction of the drift of station NP-4 corresponded to 355°, whereas in actuality the movement of the ice floe was anticyclonic, half circular. The same can be said about the drift of the station NP-4 in the April-August period in 1955 when the drift was cyclonic. It is expedient to regard the "general" direction of drift in each particular case in connection with the respective station, taking into consideration the basic stream of the ice flux in which the movement of station occurs. Besides, the "general" movement of ice, either in a straight line (along the arc of the great circle, the resultant one) or in circular direction, should be kept in mind. /8

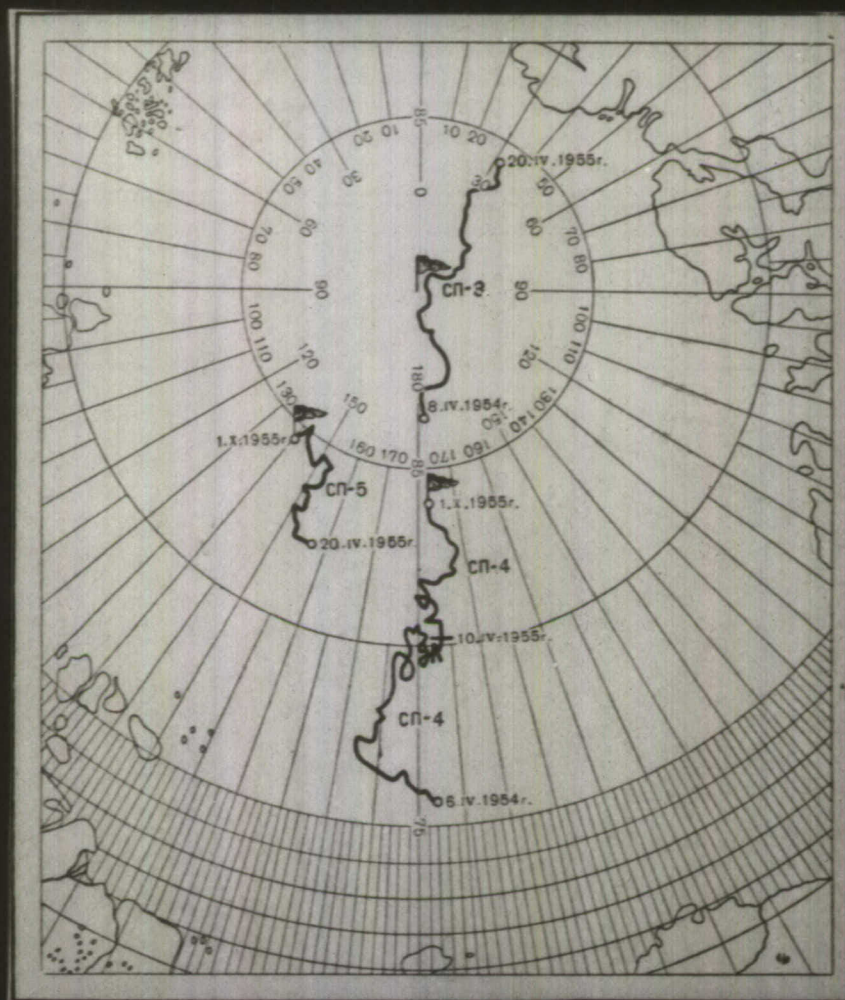
The actual extent (length) of the drift and its meandering can be judged from the continuous records of the instrument drawing the pattern on chart. In practice, however, the extent of drift is measured by adding the sections of straight lines lying between the points whose coordinates are determined astronomically. The relationship between the actual length of drift and the sum of straight lines between diurnal coordinates can be illustrated by the following example. In July 1954, M. V. Izvekov, oceanologist of station NP-4, utilizing an original method, carried out a 20-hour series of hourly and sufficiently accurate calculations of the drift speed and direction of the station. The circular course of the ice floe travelled during the 20 hours and determined by the method equalled 7.5 km. The distance between the astronomically determined points at the beginning and the end of the period (20 hours), however, equalled only 2.3 km. /9

Table 1. Coordinates of stations NP in 1954-1955
(in April-September period)

Date	NP-3 1954		NP-4 1954		NP-5 1955		NP-5 1955	
	N. lat.	E. long.	N. lat.	E. long.	N. lat.	E. long.	N. lat.	E. long.
8 April	--	--	75°48'	181°35'	--	--	--	--
10	--	--	--	--	80°39'	183°54'	--	--
15	86°20'	181°00'	--	--	--	--	--	--
20	86°36'	182°43'	75°36'	181°26'	80°46'	184°02'	82°09'	157°10'
25	84°43'	183°47'	--	--	--	--	--	--
30	--	--	--	--	80°47'	183°05'	82°15'	155°17'
10 May	--	--	--	--	80°56'	183°29'	82°39'	154°08'
20	--	--	76°20'	178°00'	81°25'	181°08'	83°00'	150°10'
25	87°01'	185°04'	76°15'	178°05'	--	--	83°00'	151°05'
30	87°02'	189°16'	77°30'	176°50'	81°14'	182°04'	82°57'	153°00'
10 June	87°05'	195°35'	76°39'	175°09'	81°35'	182°15'	83°24'	153°00'
20	87°04'	199°35'	76°51'	172°46'	81°44'	180°46'	83°49'	151°02'
30	87°35'	199°33'	77°19'	179°40'	81°52'	180°56'	83°50'	151°06'
10 July	87°44'	206°58'	77°23'	173°07'	81°49'	182°19'	84°05'	155°01'
20	88°05'	207°48'	77°31'	174°07'	82°11'	185°42'	84°22'	153°10'
31	88°42'	208°58'	77°27'	174°17'	82°14'	187°37'	84°09'	154°40'
10 August	89°00'	196°17'	78°03'	174°38'	82°16'	187°15'	84°34'	152°06'
20	89°12'	223°00'	78°57'	176°09'	82°35'	188°54'	84°37'	152°02'
31	89°27'	250°06'	79°19'	176°56'	82°41'	188°18'	84°40'	150°52'
10 Sept.	89°29'	294°15'	79°45'	176°56'	83°07'	186°59'	84°54'	147°00'
20	89°36'	284°48'	79°18'	178°12'	83°34'	184°04'	85°02'	142°30'
25	89°36'	294°48'	79°30'	178°06'	83°42'	184°03'	84°42'	141°30'
1 Oct.	--	--	--	--	84°04'	181°33'	--	--

Remark - The count of longitudes follows the circular system from Greenwich meridian eastward from 0 to 360°. Such convenient practical system has been adopted by the Arctic Institute and the main Northern Sea Route.

Figure 2. Scheme of the drift of Soviet scientific research stations in 1954-1955.



For all that, the comparative extent of a lasting drift can be determined by comparing the sections of straight lines drawn through the points that are calculated astronomically. In such a case, it is always necessary to select a section of drift, taking into consideration the set objective. For studying the processes of weekly or ten-day periods, it seems to us that diurnal coordinates can be used; for studying monthly and seasonal processes, ten-day and five-day coordinates can be used; but for studying yearly processes, monthly coordinates are in place. Regrettably, in high latitudes diurnal astronomic calculations are not always possible because of frequent fog and cloudiness.

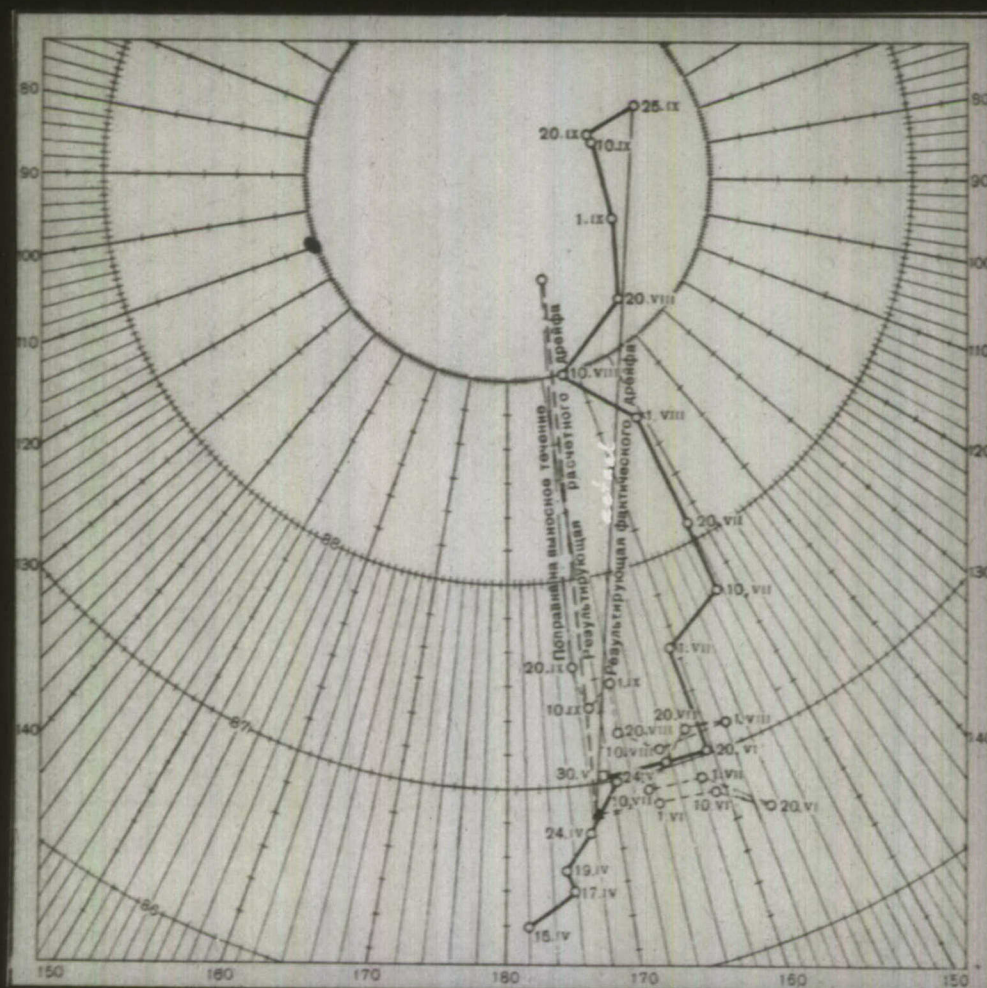
Figures 3, 4, 5 and 6 show the drift of stations NP-3, NP-4 and NP-5 with sections of lines each representing a period of ten or nearly ten days. The mean diurnal drift speeds in individual periods are shown in Table 2.

/10

Analyzing the observations on the drift of stations NP in 1954-1955, the following preliminary comments can be said:

1. In 1954 from the beginning of the drift (April) to June 20, the station NP-4 drifted strictly in the northwestern direction. When approaching the latitude 77° , the trajectory of drift turned sharply toward the right, i.e. toward "the pole of relative inaccessibility" (the course 30°). This direction was strictly maintained until the end of September. Incidentally, the original direction of the drift of station NP-4 raised in several members of the team erroneous apprehensions that the station could be carried away to the Ayon massive. It should be assumed that in April, May and the first half of June, 1954, the drift of station NP-4 practically corresponded to the general scheme of the drift (Figure 1.).

Figure 3. Drift of station "North Pole-3" in April-September 1954.



Key - The three vertical lines from left to right read as follows:

1. Correction with respect to the outgoing transporting current.
2. The resultant of the computed drift.
3. The resultant of the actual drift.

2. From the beginning of drift (April) to June 20, 1954, the station NP-3 drifted in a northeastern direction. After reaching the latitude 88° , the direction of the drift became steady toward the Greenland Sea. The direction of the drift prior to June 20 effected a premature conclusion that the station had been drawn into a circular drift. Practically, the resultant direction of station NP-3 for the entire period of April-September 1954 also corresponded to the general scheme.

/11

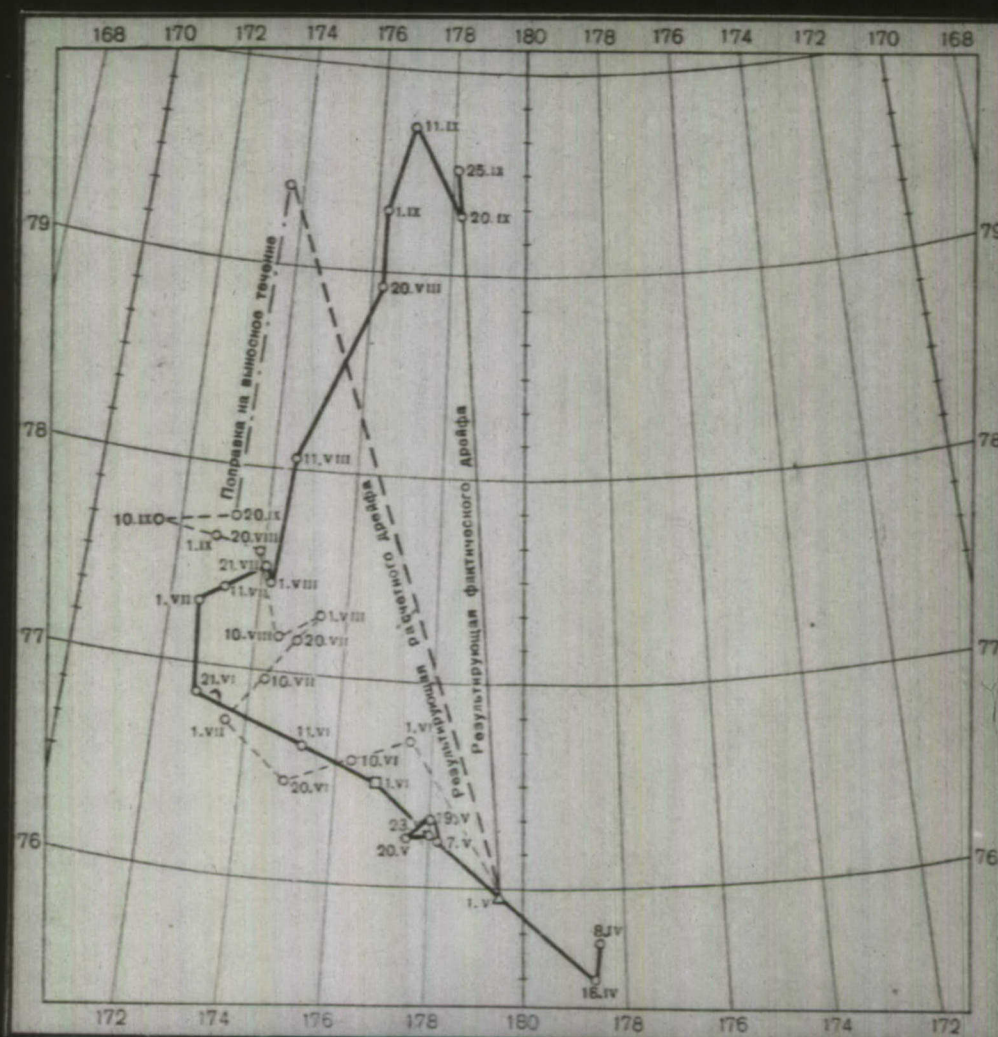
3. The mean diurnal speed and the magnitude of the drift trajectory of station NP-4 in April-September 1954 were generally 35% greater than the speed and length of the drift trajectory of station NP-3. This interesting situation will be discussed later. It should be noted that the exceeding exponents of the drift of station NP-4 over those of the station NP-3 resulted primarily from the drift occurring prior to June 20 when the station NP-4 was drifting in the belt of the continental shelf. After June 20, the difference in the length of trajectories and in the mean diurnal drift speeds of both stations decreased, mainly as a result of an increase in the speed of station NP-3. For the time lasting from May 1 to September 20, the drift resultants of both stations were practically equal (370 and 372 km). Also their directions were almost similar.

/12

4. Taking into consideration the general (resultant) direction, the movement speeds of stations NP-3 and NP-4 in April-September 1954 were on the average 10% higher than in the case of stations NP-4 and NP-5 during the corresponding period in 1955. The movement speed of ice floes, taking into consideration the sum extent along the meandering curve in 1954, was higher than in 1955, but only by 5%.

5. In 1954, the basic turn in the drift (transition from circular movement to outgoing along the arc of the great circle) of stations

Figure 4. Drift of station North Pole-4 in April-September 1954.



Key - (same as for Figure 3).

NP-3 and NP-4 occurred almost simultaneously, in the same ten-day period. After the turning point, in the second half of June, the movement speed northward increased in the case of station NP-3 and slightly decreased in the case of station NP-4.

6. In 1955, after the turning point which occurred in the third ten-day period of August, the movement speed toward north-northwest considerably increased.

7. The maximal mean diurnal speed was 11.8 km a day (on the basis of lines representing the ten-day periods), which was observed at station NP-4 in the second ten-day period of August 1954. The minimal speed was 0.2 km a day, observed at station NP-5 in the third ten-day period of June, 1955.

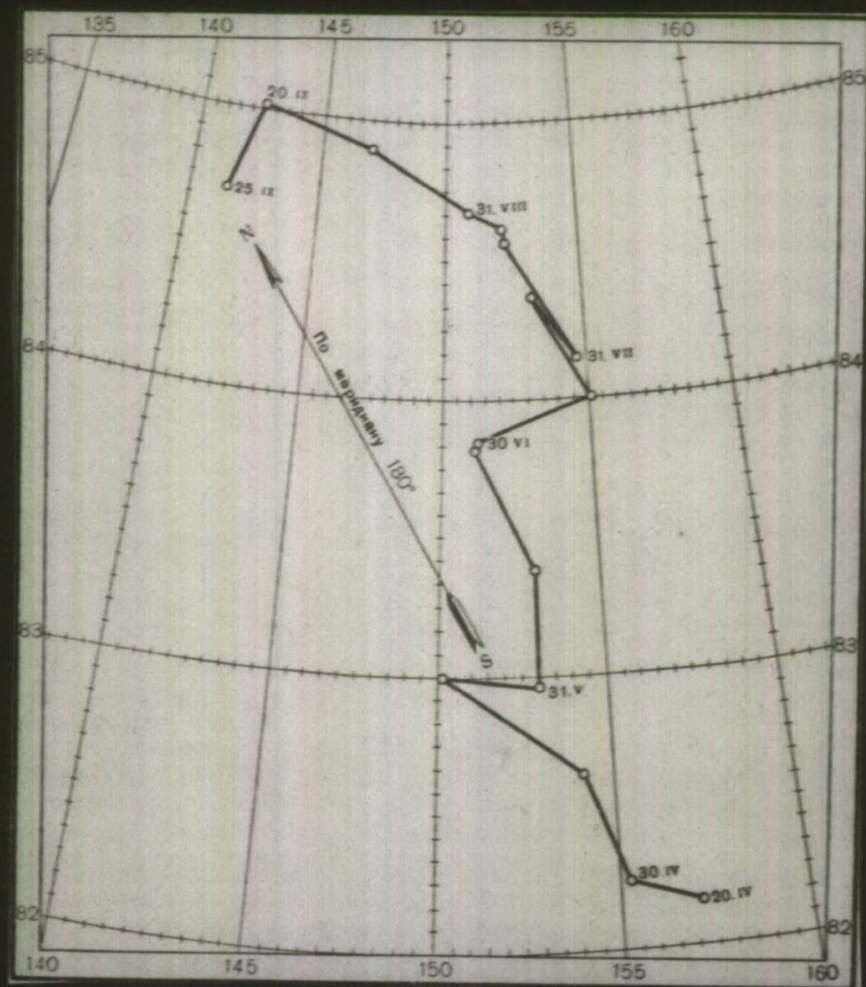
/13

Comparison of the resultants of the drifting stations was facilitated by the fact that the duration of their drift was almost similar (in 1954 NP-3 drifted 159 days and NP-4 drifted 166 days; in 1955 NP-4 drifted 174 days, NP-5 154 days). Comparison of the composite extent of drift, notably the mean diurnal speeds, would not be sufficiently objective unless the meandering of the course of each station is taken into consideration.

In order to introduce the needed corrections, we assumed a coefficient of the meandering of drift. The coefficient designates the ratio of the sum of composite lengths of drift calculated from the coordinates of ten-day periods to the length of the resultant drift in the same period of time.

The coefficient of meandering (for the period April-September) for every station was as follows: for NP-3 (1954), 1.14; for NP-4 (1954), 1.85; for NP-4 (1955), 1.63; for NP-5 (1955), 1.32.

Figure 6. Drift of the station North Pole-5 in April-September, 1955.



Key - The diagonal line in the center: along the meridian 180°.

The coefficients indicate that the course of station NP-3 was meandering.

/14

Table 2. The mean diurnal speeds of drifting stations NP in 1954-1955 (in the spring-summer period).

Drift Periods	Resulting Direction of Drift in Degrees	Magnitude of Resultant Drift in km	Mean Diurnal Speed in km	Remarks
Station NP-3, 1954 (Fig.3)				
April 15-June 20	45	160	2.4	Tendency toward circular anticyclonic drift
June 20-Sept. 20	347	360	3.8	Steady movement northward
Entire period	7	520	3.3	
According to length of resultant for entire period	7	456	2.8	
Station NP-4, 1954 (Fig.4)				
April 8-June 21	300	336	4.5	Movement in direction of Ayon massive
June 21-Sept. 20	30	392	4.3	Steady movement toward the pole
Entire period	348	728	4.4	
According to length of resultant for entire period	348	394	2.3	
Station NP-4, 1955 (Fig.5)				
April 10-Aug. 10	15	408	3.3	Tendency toward circular anticyclonic drift
Aug. 10-Sept. 30	328	212	4.2	Fast movement in northwestern direction
Entire period	352	620	3.6	
According to length of resultant for entire period	352	380	2.2	
Station NP-5, 1955 (Fig.6)				
April 20-Sept. 21	355	584	3.8	Movement northward along axis of Lomonosov range
According to length of resultant for entire period	355	366	2.4	

Generally, however, the course of the stations drifting with the outgoing stream of ice (stations NP-3 and NP-5) was straighter than that of stations drawn into the periphery of the circular anticyclonic movement. The fact can, evidently, be explained by two factors:

(1.) In the zone of the outgoing ice movement, where stations NP-3 and NP-4 were drifting in the spring-summer period, the surface currents were rather stable. Approaching the Papanintsev Strait, the stability and speed of the current increases. Such a hydrodynamic situation is disrupted only by exceptional conditions. Such conditions were present for station NP-3 in the spring of 1955, when a huge expanse of ice fields moving toward the strait during the winter in 1954-1955, could not pass freely through the strait, which blocked and considerably retarded the transport of ice.

(2.) In the peripheral zone of the circular anticyclonic movement, into which the station NP-4 had been drawn in the the /15 spring-summer periods of 1954 and 1955, the wind regime happened to be very unstable. The area was affected by frequent Pacific cyclones coming from the south, by Atlantic cyclones coming from the west, and by the so-called Yakutian cyclones coming from the northwest. The cyclones were accompanied by frequent shifts in the direction and velocity of wind. The most shifting wind regime occurred in the area situated to the southwest of the anticyclonic drift circle which appears to be the area for the mentioned cyclones; here was the station NP-4 in 1954. In the area located to the west of the center of the drift circle, however, where was the station NP-4 in 1955, were active only the high latitude cyclones, and the shifts in wind regime were smaller.

Taking into consideration the sum of the composite extent of drift lines drawn through the points of diurnal coordinates, the coefficient of meandering will be greater than in the case of the coordinates of ten-day periods. Table 3 lists the data of the composite extent of monthly drift of station NP-4 in the April-September period of 1955, which was computed by A. V. Teologov, making allowance for diurnal meandering.

Table 3. Drift of station NP-4 in the April-September period of 1955, considering its meandering on the basis of diurnal data concerning coordinates.

Month	Total composite length of drift in km	Length of drift resultant in km	Direction of drift in degrees	Coefficient of meandering (on basis of diurnal data)
April	98	26	320	3.77
May	206	47	299	4.38
June	175	72	342	2.46
July	198	108	65	1.83
August	222	58	20	3.83
September	223	183	340	1.22

The data listed in Table 3 show that the meandering of drift increases considerably in transition periods from one season to another, which are characterized by most unstable winds as to their direction and speed: i.e. in April and May (transition from spring to summer) and in August (transition from summer to autumn).

On the contrary, during the months when the drift resultant appears to be of maximum length, the coefficient of meandering is of minimum magnitude.

Of great practical interest is the comparison of the drift of stations NP in 1954-1955 (of course, to a degree at which such comparison is possible geographically) among themselves and with the data relative to the drifts of the Fram (1893-1896), G. Sedov (1937-1940), NP-1 (1937) and NP-2 (1950-1951).

Inasmuch as the expeditions drifted in various areas of the Arctic Ocean, the drifts, when plotting Table 4, were arranged in accordance with these geographical characteristics: the drifts in the belt of the continental shelf and in the deep-water area of the ocean.

Examining the right- and left-hand parts of Table 4, one can see that the mean diurnal speeds of the drifting stations NP-3 and NP-4 in 1954, as well as those of stations NP-4 and NP-5 in 1955, exceeded considerably the speeds of all stations and expeditions /16 that had drifted in the past years. The speed of station NP-3 exceeded the drift speed of station NP-1, although in the given time period the station NP-3 was farther from Papanintsev Strait than the station NP-1.

Table 4. Comparison of mean diurnal drift speeds in various areas of the Arctic Ocean.

Drift in deep-water areas of the Arctic Ocean			Drift in the belt of continental slope of the Arctic Ocean		
Station (ship) and the area of drift	Period	Mean diurnal speed km/day	Station (ship) and the area of drift	Period	Mean diurnal speed km/day
Fram, polar region along the parallel 85°	1.I 1895 1.I 1896	1.6	Fram, interior part of the Laptev Sea	1.I 1894 1.I 1895	2.1
NP-1, polar region between parallels 90° and 87°30'	21.V-1.VIII 1937	2.8	G. Sedov, over the underwater ridge north of Novosibirskiye Ostrova	2.III-5.X 1938	3.8
G. Sedov, polar region along parallel 86°	5.X 1938- 17.VI 1939	2.3	NP-4, along the continental slope north of the East Siberian Sea	8.IV-20.VI 1954	4.5
NP-2, north of the Chukchi Sea	1950-1951	1.5	NP-5	20.IV-20.VIII 1955	3.9
NP-3, polar region	15.IV-20.IX 1954	3.3			
NP-4, area of the pole of relative inaccessibility	10.IV-30.IX 1955	3.6			
The mean speed		2.7	3.5		

Remark: Data listed in table were calculated on basis of trajectories of drifts drawn through points of coordinates for ten or nearly ten-day periods.

From the limited number of cases it is, however, possible to draw another interesting conclusion - namely, that the mean drift speed along the Eurasian part of the continental shelf is greater than in the deep-water region of the Arctic Ocean.

Loop-Shaped Evolutions at Ice Drift

When elucidating the external characteristics of ice drift for lasting periods, it is of great interest to investigate the loop-shaped evolutions of ice floes. The resultant movements along such loops equal zero.

Since it is possible to compute the resultant of wind drift, one can determine the direction and speed of the so-called steady state surface current for the period of drift moving along a locked curve. In this case, as was already suggested by Nansen, the magnitude of the current resultant can be validly regarded as equal to the resultant of wind drift, but the direction of the /17 current resultant as opposite to the direction of wind drift.

In April-September 1955, the drifting station NP-4 formed nine loops (on the basis of diurnal coordinates), (Fig. 7a and 7b). The loops can be divided into two basic types: the loops of anti-cyclonic movement (A, three cases) and the loops of cyclonic direction (B, six cases).

The specific weight of such evolutions, not having results in the movement along the general line, can be seen from the fact that out of 174 days spent by drifting station NP-4 in 1955, 87 days, i.e. 50% of the total time, were spent for loop-shaped movements. Consequently, when computing ice drift in the conditions of a steady state wind regime (for the case when the formation of loops

cannot be expected on the course of drift), one should not be guided by the mean speeds or the mean wind coefficients found for a lasting drift. The mean magnitudes that are taken into consideration must be multiplied twice.

Table 5 shows the data concerning the resultants of a computed wind drift for the period of time when loop-shaped movements were observed.

Table 5. Computation of wind drift, the direction and speed of current at a time when the station NP-4 performed loop-shaped movements (in April-September 1955).

Period	Resultant direction of wind (°)	Mean speed of wind along resultant m/sec.	Wind coefficient of drift	Computed direction of wind drift (°)	Magnitude of wind drift for period (km)	Computed direction of current (°)	Mean diurnal speed of current (km)
2-20.IV (9 days)	3	0.2	0.010	33	1.53	213	0.17
0.IV-8.V (18 days)	209	1.2	0.011	259	20.52	79	1.14
15.V-2.VI (17 days)	54	0.4	0.010	84	6.78	264	0.34
16.VI-27.VI (11 days)	167	1.4	0.011	197	14.6	17	1.33
26.VI-4.VII (8 days)	50	0.7	0.012	80	5.92	260	0.74
24.VII-28.VII (5 days)	29	2.6	0.018	59	20.20	239	4.04
1-10.VIII (10 days)	121	1.2	0.015	151	15.60	331	1.56
3-18.VIII (5 days)	89	1.3	0.013	119	7.30	229	1.46
4-8.IX (4 days)	157	0.45	0.010	187	1.52	7	0.38

The magnitudes of wind coefficients were adopted by us from the scientific operative means worked out by the Arctic Institute. Of course, we took into consideration the predominant concentration of ice that was observed in the respective time periods in the area of station NP-4. In April, May and June, 1955, the concentration of ice in the area /18 of station NP-4 equalled 9 to 10 balls; in July it was 7 to 8; in August 8 to 9; in September 9 to 10 balls. As regards the age, polar ice prevailed. The angle of drift declination from the wind direction was assumed to equal 30° to the right.

The computation results presented in Table 5 show that the "permanent" surface current of the area crossed by the drifting station NP-4 in 1955, when examined by periods ranging from several days to 2 to 2.5 /19 weeks, are subject to considerable variability which, evidently, can be explained by causes of a greater order than are the diurnal synoptic processes. The fact that in six instances out of ten the loops are orientated toward the west (from the 180° meridian) indicates the presence of deflecting action of current during the formation of the loops.

Why are the loop-shaped curves of drift formed? It is not possible for us to answer now. It is of great interest to examine each of the nine cases in connection with the synoptic charts and the trajectory maps of basic formations as regards the location of station NP-4. Regrettably, the materials were not at our disposal.

/20

Certain Ideas Concerning the Causes of Lasting Impairment of Ice Conditions in the Northern Sea Route in 1954 and 1955.

The spring months (April-May) of 1954 were characterized by a positive anomaly of air temperature along the entire Northern Sea Route. In June and July the air temperature was nearly normal, the difference not exceeding 1° . In August the air temperature, remaining nearly normal over the Kara and the Laptev seas, was somewhat below normal over the East Siberian and the Chukchi seas.

Figure 7a. Loops described by the drifting station North Pole-4 in April-July 1955.

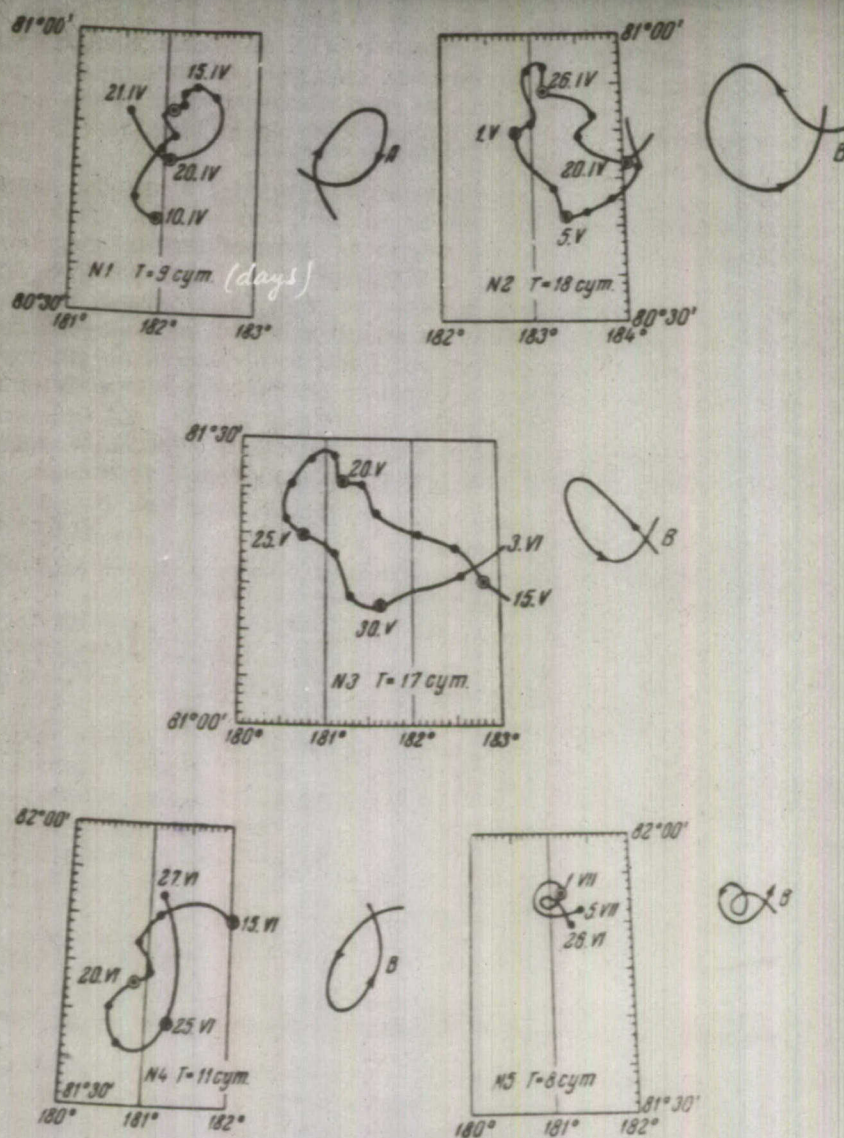
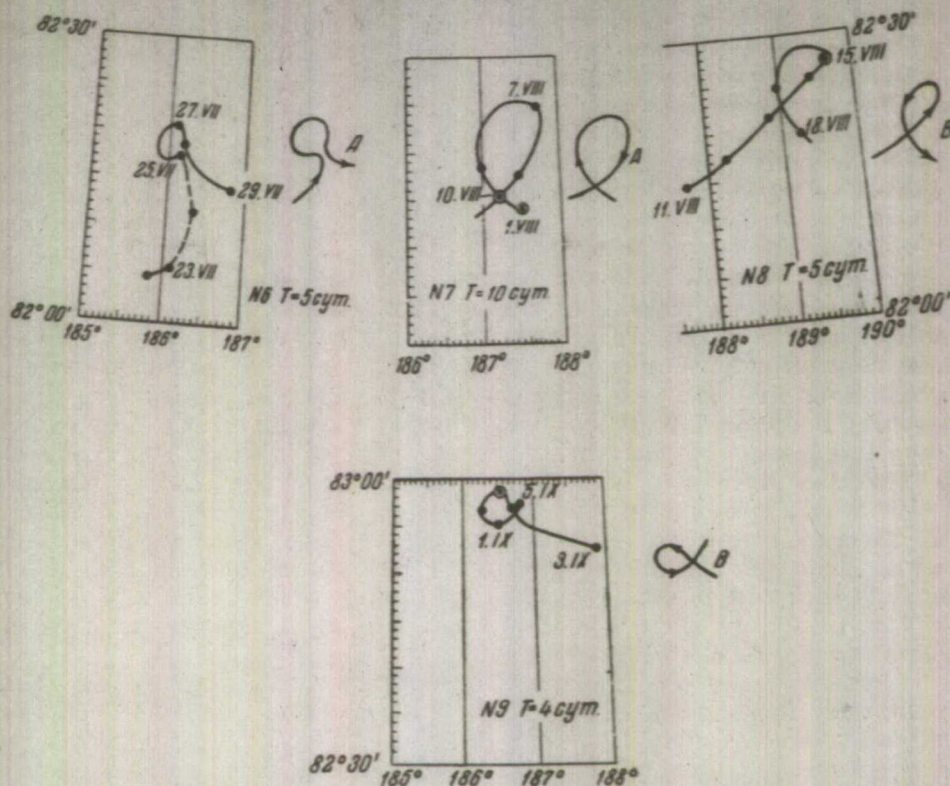


Figure 7 b. The loops formed by the drifting station North Pole-4 in July-September 1955.



With respect to ice conditions, the beginning of the summer season in 1954, taking into consideration only the ice inertia, promised a favorable development of the process of ice destruction and displacement, which corresponded to the thermal regime of atmosphere and to ice conditions on the Northern Sea Route.

Thus, for instance, the breaking of the winter fast ice in the Chukchi Sea, in the eastern part of the East Siberian Sea and in the Vil'kitskiy Proliv (V. Strait) was observed 5 to 15 days before the mean dates, but in the Laptev Sea it was at a date near the normal. Only in the western part of the East Siberian Sea the breaking of winter fast ice was delayed by 3 to 8 days. The iciness of the Arctic seas, i.e. the degree to which they were covered by ice, was nearly normal, or somewhat smaller, in the first navigational month (July).

Thus, the beginning of navigational period, if one takes into consideration only the local thermal and dynamic processes affecting directly the Arctic seas, promised comparatively favorable navigational conditions. In the first half of August, however, the iciness of the Chukchi and East Siberian seas began to increase. The phenomenon was accompanied by the creation of the Wrangel' ice massif¹, the sloping of the Ayon ice massif and by general worsening of navigational conditions in the seas. The heavy polar ice floes, sloping from the north toward the Chukchi coast were not infrequently difficult to master even by icebreakers. The worsening of ice conditions continued practically to the middle of September when, by the action of the warm current coming from the Bering Sea and by local warming up, the ice masses arriving from the north were either weakened or destroyed.

¹ Editor's Note - This word is used by the Russians to indicate a large and stable pack which tends to recur in certain localities year after year.

It is noteworthy that the station NP-4, being at the time at the boundary meridians between the Chukchi and the East Siberian seas, to the north of the seas, and the station NP-3, approaching the geographic North Pole, were drifting northward with considerable speed. During the entire summer 1954, the resultant drift vectors of stations NP-3 and NP-4 were directed from the eastern seas of the Northern Sea Route toward the north. Such parallel drift of stations separated from each other by a distance of 1100 km was undoubtedly accompanied by a transfer of vast ice fields; the southern edge of the field (possibly giant belts) was near the original point of the drifting station NP-4 in April, but the northern edge had to move southward from the position of station NP-3 on September 20, 1954. The formal evaluation of the facts permitted the formation of views on favorable ice drifting conditions in high latitudes. As we shall later see, the conclusion was false.

In 1955, during the summer months, as late as the middle of August the ice did not leave the Chukchi coast as usual, but remained packed along the coast. Such ice conditions obstructed the beginning of active operations in conveying ships from the east to the ports of the East Siberian and the Laptev seas.

/21

The analysis of local factors that determine ice condition, such as the air temperature, the tension of heat currents coming from the Bering Sea, the masses of ice at the end of winter, and lastly, the wind regime in June, July and at the beginning of August, failed to provide a satisfactory explanation as to the causes of delay in freeing the coast from ice.

It was already in 1954 when we strove to investigate the possible effect of ice displacements in high latitudes on the formation of ice conditions in the coastal areas. The work of two drifting stations in the Central Arctic permitted us to investigate the problem more thoroughly. We based our work on the following hypothesis:

(1) the general scheme of ice drift in the Central Arctic appears to be a climatologic resultant of action caused by the circulation of atmosphere and the surface current against the ice cover, which progresses along the arc of the great circle, tending into the Greenland Sea, whereby the speed of the current is minimal in the Canadian-American sector. In conjunction with it, in the Canadian-American sector of the ocean, the polar maximum and the corresponding winds constitute the most stable factor during the major part of the year. As a result of the predominant influence of the factor in this sector, not only is the ice drawn into anticyclonic drift but, evidently, also sufficiently thick surface layers of the ocean which also lie in the anticyclonic system of the so-called permanent (steady state) circular current. On the western side of the system, where the station NP-4 drifted in 1954 and 1955, the current is directed from south to north. In the area of the ocean adjacent to the Papanintsev Strait, the major role in the transport of ice belongs to the accelerating transporting (outgoing) current;

(2) at the presence of lasting dislocations in the usual scheme of the displacement of baric atmospheric centers over the Arctic Ocean, and especially in case the Spitzbergen maximum of atmospheric pressure sets in or in other baric conditions, the influx of Atlantic waters into the Arctic Ocean through the Bering Sea and the transport of Arctic waters southward through the Papanintsev Strait diminish. These circumstances cause a slow-down in the ice transport from the entire expanse of the ocean toward the Papanintsev Strait. When the dislocations are lasting, the major part in the formation of ice conditions and drift over the entire surface of the ocean is played by local circulations of the atmosphere. Computations of ice drift by the "Zubov method" in such circumstances become completely dependable;

(3) the replacement of more frequent types of atmospheric circulation (the types, in fact, create the drift pattern shown in Figure 1) by less common types of circulation, whose direction is usually reversed, is

accompanied by changes in the tension of water flow in the ocean, no matter whether they are incoming or outgoing. In the final analysis, the changes manifest themselves in the form of outgoing pulsations.

The extent of possible fluctuations in the transport of ice from the Arctic Ocean into the Greenland Sea can be sufficiently great and, according to our calculations, it can reach a million square kilometers.

In May 1954, during an aerial ice reconnaissance in the area lying between the North Pole and the Greenland Sea, for the first time we observed that the central part of the ocean was covered by a compressed continuous ice cover, that the temporary bases of the high latitudinal aerial expedition established in the area of North Pole were drifting slowly, but that in the northern part of the Greenland Sea was a reversed rare phenomenon: the East Greenland ice flow did not exist.

/22

Almost no old ice could be seen in the entire expanse between Greenland and Spitzbergen nor in the region lying nearly 100 miles to the north of the Papanintsev Strait; the ocean was covered by young ice. During the time (April 1954) the winds of the southern quadrant lastingly prevailed over the Papanintsev Strait. In the eastern half of the Barents Sea, where northeasterly winds prevailed, an increased iciness was observed.

These were the basic aspects of the working hypothesis adopted by us when solving the concrete problem on the causes for the worsening of ice conditions in the eastern sector of the Northern Sea Route in 1954 and 1955.

In the spring and summer months of 1954, the water expanse of the Arctic Ocean was under the action of the centers of atmospheric circulation whose location and displacement was geographically unusual. The immediate polar area and the regions of the ocean adjacent to the Beaufort, Chukchi, and East Siberian seas were under the impact of active cyclones

that had penetrated the high latitudes from the Okhotsk and Bering seas. Over the Kara Sea and the sector adjacent to the Atlantic Ocean, anti-cyclonic wind regime predominated over the Barents Sea, which is usually crossed by the trajectories of the cyclones of North Atlantic origin, the cyclonic activity was weakened; only a few cyclones penetrated to the east of Novaya Zemlya.

The analysis of maps depicting the displacement of the centers of atmospheric circulation, and of the mid-seasonal map of atmospheric pressure for the summer period of 1954, permits a close approach to elucidating the causes for the worsening of ice conditions in the given sector of the Northern Sea Route in the July-August period of the year. The analysis discloses the following basic peculiarities of the baric relief of atmosphere, which are reflected in the peculiar drift of ice:

(1) the transport of ice from the Arctic Ocean into the Greenland Sea in summer 1954 was retarded in connection with the prevailing of wind whose direction was against the outgoing flow of surface waters and ice (let us recall the observations of aerial ice reconnaissance in the area of Papanintsev Strait in April 1954);

(2) in the Canadian-American sector, where throughout the summer the isobars were steadily directed from the Bering Strait toward Greenland, the ice found in the regions adjacent to Alaska was transported to the north. In connection with it, concentration and compression of drift ice, and frequent stoppages in the drift, were observed along the northern coast of Greenland and the islands of the Canadian Archipelago. Aerial ice observations showed that the concentration and compression of ice at the approaches to Greenland and Elsmire Land occurred already in April-May 1954. During the summer 1954 the drifting stations NP-3 and NP-4 were carried by a current that transported the ice across the Arctic Ocean;

(3) from the area of the geographic pole, the ice flow (current) is forced to move toward the East Siberian Sea, the Vrangeli Islands and the western part of the Chukchi Sea. The presence of the current encompassing a belt of the ocean more than 500 km wide explains the accumulation of ice along the Chukchi coast in the summer of 1954. In connection with the fact that there existed in the immediate area of the North Pole, a certain, although weakened, outgoing current of surface waters directed toward the Greenland Sea, the wind drift in the area was somewhat reduced. Therefore, because of differences in the speed of drift in the southern and the northern sections of the pressure belts, there were created breaks in the concentration of ice cover which was very dense indeed;

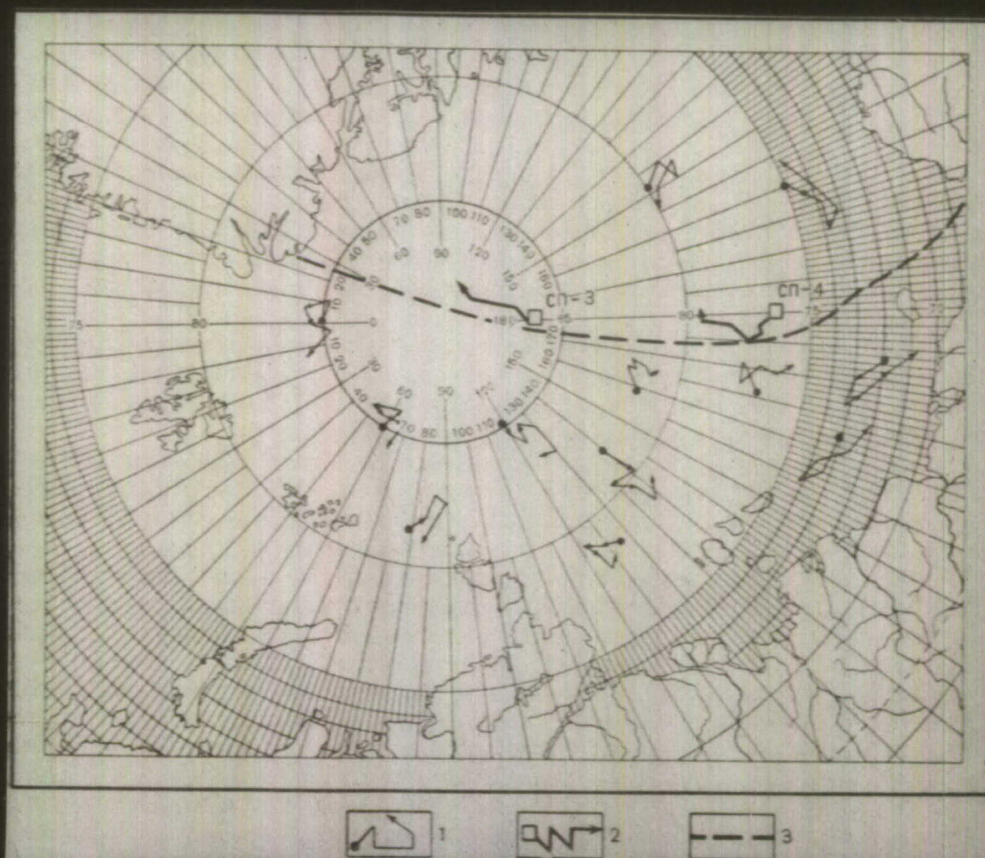
/23

(4) around the islands of Severnaya Zemlya such conditions were created that the ice was brought from the Kara Sea toward the north and pressed to a certain degree against the west coast of the archipelago. The same anticyclonic system of drift that furthered the destruction of the Taymyr massif sustained the concentration of ice at the central meridians of the northern part of the Laptev Sea.

The outlined conclusions are based not only on the examination of peculiarities of the baric relief according to the mean pressure chart but also on the computation of ice displacements in the Central part of the Arctic Ocean according to the "Zubov law". The computation results are shown in Figure 8, expressing them in the form of drift trajectories plotted on freely selected points of ice cover.

A more detailed examination of the computed drift trajectories helped find out that the drift was irregular, i.e. pulsating, during the season that is discussed. Thus, the major faltering of the oceanic ice in the area of Ayon massif and from there in the Long Strait occurred in July,

Figure 8. Computed displacements of ice in the Arctic Ocean in the spring-summer period of 1954.



Key - 1-monthly vectors of isobaric drift in May-September;
2-the same of the actual drift of NP-3 and NP-4;
3-the division of the drift.

August and September. The declination of ice drift toward the south in the area lying to the west of the drift divide began in June. When in September the ocean ice began to drift into the Kara Sea, and into the Laptev Sea, the outgoing regime of drift became established.

In the area of Papanintsev Strait, only in June (during the period from May to September) the drift vector was directed toward the Greenland Sea.

The conclusions derived from the computations of drift during the spring-summer season in 1954 were verified by a number of aerial reconnaissances in high latitudes.

Figure 9 shows the comparison of the actual position of ice barriers and the boundaries of ice massifs in the Northern Sea Route in the first half of September with computation results. The chart discloses the influence of a peculiar synoptic situation on the ice. The actual status of ice and the direction of its transport are in sufficient agreement with the computations.

Thus it is possible to explain the seemingly paradoxical blockade of the Chukchi coast by ice masses brought from the north while stations NP-3 and NP-4, located on the same meridians, were drifting to the north with a record speed.

In 1954, the ice situation in the Arctic Ocean can be regarded as an example of the dislocation of general scheme of ice drift. The analysis of the example shows that, in examining the question on ice conditions in the Arctic Seas along the Northern Sea Route one must take into consideration the displacement of ice in high latitudes and, basically, in the area of transport - the Papanintsev Strait. The synoptic charts and drift characteristics of stations NP supply the needed material for such analysis.

It should be noted that, when examining the computation charts of the past years, only the chart of the summer of 1933 is analogous to the chart of the summer of 1954. Let us recall that in 1933 the ice blocking the Chukchi coast crushed the steamship Cheliuskin.

In the spring-summer period 1955, as stated above, again an unusual stability of the continuous ice cover was observed along the coasts of the eastern part of the East Siberian Sea, in the Long Strait, and in the western part of the Chukchi Sea. The ice conditions created here corresponded well to the ice processes occurring in high latitudes. It was already pointed out that during the entire summer period and until the end of September 1955 the resultant direction of drift and individual detours of the trajectories of drift did not exceed the limits of the characteristics of ice that drifts in a system of extreme circular flows of the anticyclonic ring shown in the general scheme of drift (Figure 1.).

However, the examination of monthly drift vectors of station NP-4 from April to September 1955 demonstrated that the movement speed of the station in a direction that might be considered "general" for the station NP-4 in the given area of anticyclonic flow was not uniform. When moving across the western section of the anticyclonic ring, between parallels 80 and 85°, the general direction was north-north-east (15° with respect to the meridian 180°). At the time, the resultant direction of our ice floe was 352°, which differed little from the general direction (23°). The projection values of each monthly drift vector of station NP-4 on the meridian 180°, i.e. the magnitudes of progressing movement along the anticyclonic ring, were as follows /25 (in km): in April - 18; in May - 42; in June - 45; in August - 32; in September - 160.

Such significant fluctuations in the speed of progressing ice displacement (pulsation) could not be explained only by shifts in wind regime.

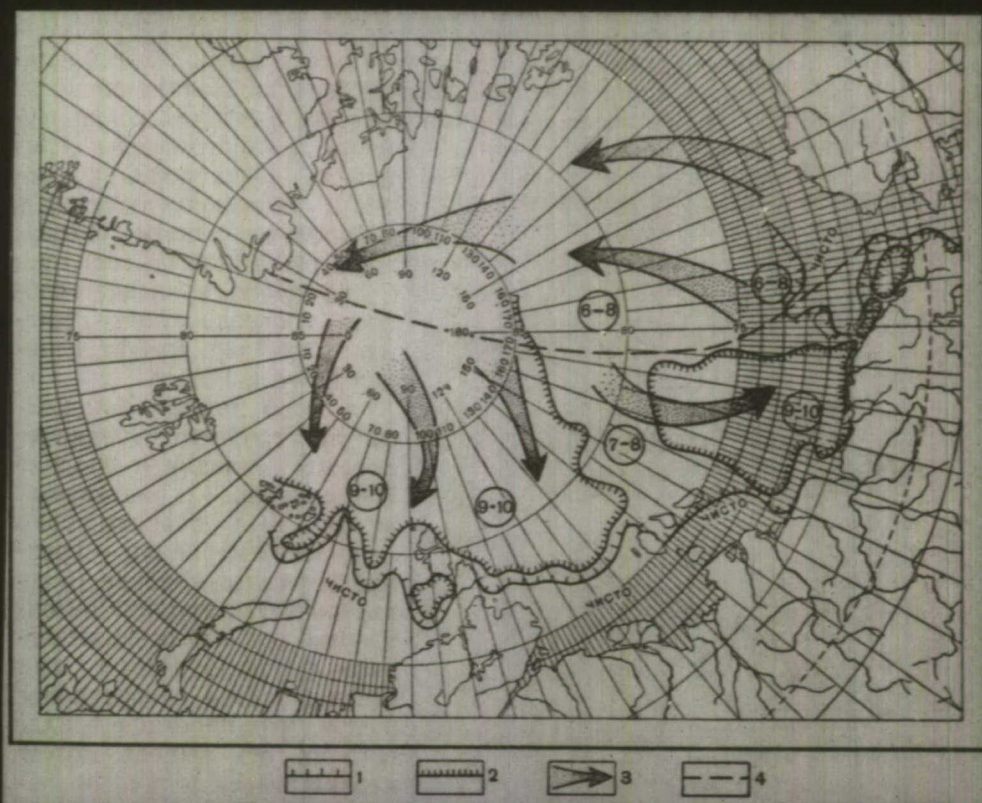
Inasmuch as the composite ice displacement in any sufficiently long time period appears to be the resultant of two components - the displacement as a result of wind action and as a result of ice transport by surface currents - we made corresponding computations for each month.

At the selection of wind coefficient, the actual ice concentration in the surroundings of station NP-4 having a radius of 50 miles was taken into account; the declination angle of ice drift from the direction of wind was assumed to equal $+30^\circ$. The current vectors were computed from the composite drift vector of wind drift. The results of the computation, expressed as vectors of the resultant surface current for each month in the same scale as the vectors of wind drift, are shown in Figure 10. Examining the figure, one can see that in July and August the retreat of ice from the shore northward must have been at a minimum. Further, the weakening of the south current and the lateral (from west to east) transport of ice by the wind in July, as well as a complete cessation of outgoing current, which was /26 even accompanied by the appearance of a weak current from north to south in August, also did not contribute to the recession of ice from the Chukchi and Alaskan shores.

It is evident that a more detailed analysis taking into consideration all the local factors that participate in the formation of ice conditions on the Northern Sea Route will permit a more complete formulation of the role played by ice displacements occurring in high latitudes in this process.

An examination of the lines of ice transport by currents in 1955 led to the conclusion concerning the relative conservativeness of the direction of surface current in the area of drifting

Figure 9. The basic directions of ice displacement in the Arctic Ocean during the navigational period in 1954.



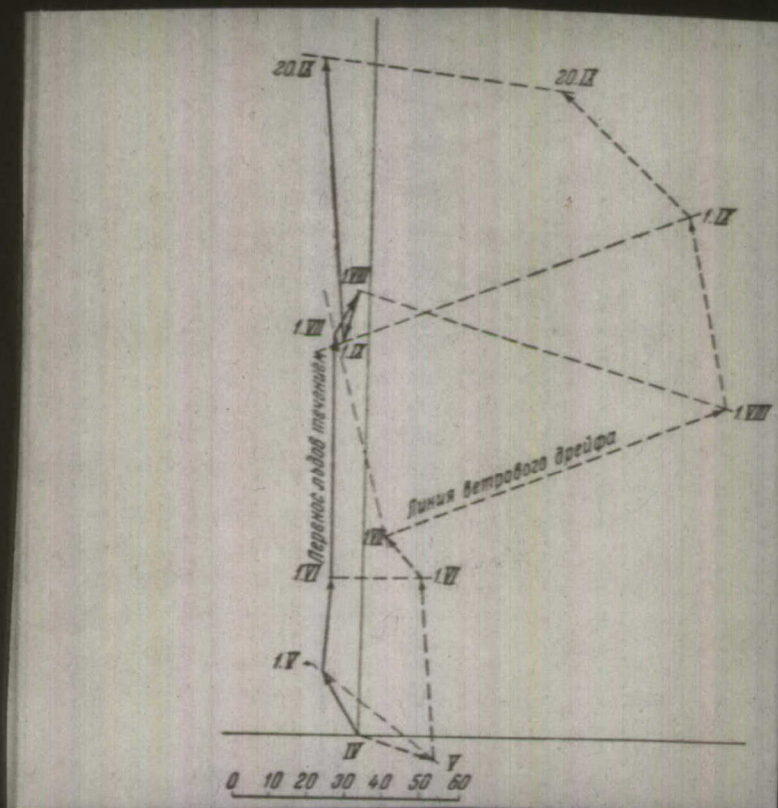
- Key - 1-the southern ice rind in the first half of September;
 2-the outer boundary of concentrated ice (massif, the degree of concentration exceeding 9 balls);
 3-the basic direction of ice displacement in July-September;
 4-the basic divide of drift.

station NP-4. In our opinion, such stability in the direction of water flow is caused by the fact that the compensating flow from the Arctic Ocean into the Greenland Sea was active continuously. The speed of the flow, however, in association with fluctuations in the atmospheric circulation in the area of outflow (Papanintsev Strait) was not uniform and was shifting from month to month. Taking into account the interlinking of the speed of outflow through the Papanintsev Strait with the speed of outgoing current in the central section of the ocean, we verified the causes for pulsations in the speed of surface currents in the area of drifting station NP-4 in 1955.

For the purpose, the gradient of semimonthly pressure in the Papanintsev Strait was computed. The gradient vector was laid off on the zero meridian - the middle meridian of the strait (in the northern part of the strait it was at the same time the axis of outgoing flow). The computation was based on the assumption that the projection of gradient on the axis of outflow can characterize the degree of retarding or accelerating effect of local winds on the speed of outgoing flow in the Papanintsev Strait and in the adjacent areas of the Greenland Sea and the Arctic Ocean.

Figure 11 shows shifts in the tension of wind action in the Papanintsev Strait (projection of the pressure gradient vector over the axis of transport) and in the speed of current in the area of drifting station NP-4 in the April-September period. The identity in the course of the two processes is conspicuously shown in Figure 11. This convinces us of the correctness of the working hypothesis concerning the unity of dynamic processes in the Arctic Ocean: the displacement of ice, of surface currents and the circulation of the atmosphere.

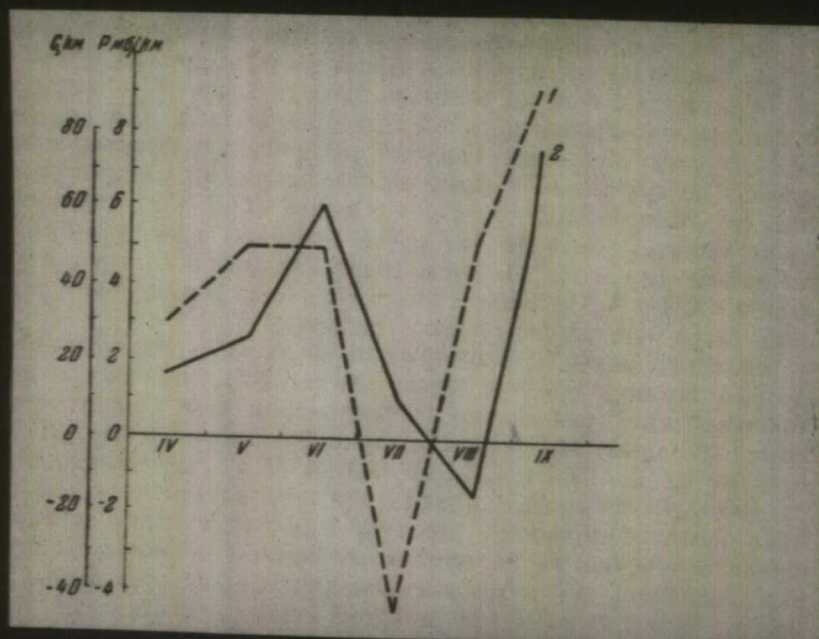
Figure 10. The components of ice transport by the wind and current in the area of station North Pole-4 in April-September 1955.



Key - The vertical line on the right-hand side reads: transport of ice by the current.

The diagonal line reads: the line of wind drift.

Figure 11. The interlinking of outgoing air flow in the Papanintsev Strait and with current pulsations in the area of drifting station North Pole-4 in April-September 1955.



Key - C, KM-the vector of the transfer of station NP-4 by the current in km;
 PM/KM-the projection of the vector of outgoing air flow in the
 Papanintsev Strait over the directions of transport (N→S);
 1-the air flow;
 2-the current

In this case, we regard the local circulation of atmosphere in the area of ice outflow as a potent factor which is able to correct the speed of outflow to a considerable degree. The first more potent factor determining the transport of ice and surface waters from the Arctic Ocean is the inflow of Atlantic bottom waters into the ocean. The study of the nature of this phenomenon, and especially the study of fluctuations in the tension of the Gulf Stream, is thus inter-linked with the solution of prognostic problems for the Arctic Ocean.

The Possibility of Forecasting Ice Displacements in High Latitudes of the Arctic Ocean

Not so long ago, during the drift of station NP-1 or the icebreaker G. Sedov, the forecasting of general, principal characteristics of lasting ice drifts in the Arctic Ocean was extremely difficult, mainly because of lack of knowledge of the general scheme of drift. Later, extensive observations on ice distribution in the regions of high latitudes adjacent to the Northern Sea Route permitted the clarification of these characteristics. The more possible directions of drift and its mean velocities were determined. The knowledge of the characteristics was, however, more or less satisfactory only with respect to the Eurasian sector of the ocean. As regards the Canadian-American sector, our knowledge of the character of local /28 ice circulation remained extremely limited until the observations on the drifting ice islands T-1, T-2 and T-3 were published; of special significance were investigations of the drift of the ice floe on which the station NP-2 was active in 1950-1951.

At the present time, the practical significance of forecasting ice drifts in high latitudes of the Arctic Ocean has increased tremendously, insofar as the conclusions based on such forecasts are needed for solving practical navigational problems on the Northern Sea Route. The forecasting of the drift of large ice masses in the central part of the Arctic basin (and the drift of stations NP) has

become an essential part of general prognosis on ice conditions on the Northern Sea Route as they may affect navigation; practically, this aspect forms the basis for general ice forecasting.

In 1954 we attempted to compute the drift of stations NP-3 and NP-4 in the May-September period. The solution was based on the computation of wind drift calculated from prognostic charts concerning the mean monthly pressure, which were prepared by G. Ia. Vangengein and A. A. Girs of the Arctic Institute, and on computation data concerning the direction and mean speed of surface currents in various regions of the ocean. The latter data we obtained jointly with D. B. Karelin in 1944-1945 by means of comparatively simple plottings.¹

The computation of wind drift was done in accordance with "Zubov's law" by the use of wind coefficients, as was the practice of the Arctic Institute.

Figures 3 and 4 show the prognostic drift vectors of stations NP-3 and NP-4 for the entire period from May to September 1954, in addition to the actual drift of the stations. The dotted lines show the computed trajectories of wind drift which were based on monthly charts of mean pressure. The errors of the computed resultant drift vectors in comparison to the actual data were found out: with respect to the direction of the resultant drift for station NP-3 it was: -9%; for station NP-4, -18% (the minus mark denotes that the respective drift appeared to be to the left, westward from the actual position); with respect to the magnitude of the resultant, the error for station NP-3 was +28%; for station NP-4, +9% (plus mark denotes that the magnitude of computed vector was smaller than the actual magnitude).

¹P. A. Gordienko and D. B. Karelin. The problems of ice displacement and distribution in the Arctic Basin. Problemy Arktiki (Problems of the Arctic) no. 3, 1945.

The errors (of which only one: the magnitude of the resultant drift of station NP-3 exceeded 20% of the phenomenon itself) are such that formally the forecasting can be regarded as satisfactory. At the present time, however, in the light of careful analysis of the course of drifting stations NP-3, NP-4 and NP-5 in 1954-1955, we have to admit that the prerequisites of prognosis and the conclusions from it are unsatisfactory. For instance, the introduction into the computation of the mean climatological speed of current, which did not correspond to the baric situation which was expected at the circulation of the atmosphere that was setting in was incorrect. Now we know that, with the development of cyclonic activity between the Bering Strait and the Greenland Sea and at the eastern location of the stations as regards the lines of the drift divide (and water divide), we had to select a greater than average speed of the surface current.

The conclusions based on the forecasting of the displacement of the two stations northward must be considered unsatisfactory. The conclusion was not ensued by a prognosis of ice displacements in the adjacent, more western area of the ocean, although the displacement must have exercised a substantial influence on the formation of ice condition on the Northern Sea Route. The deficiencies in the prognosis make it altogether unsatisfactory. /29

When preparing forecasts of ice displacements in any part of the Arctic Ocean, it is necessary to examine the possible changes of the current regime in the entire central sector of the ocean and in the outgoing area, to analyze the interaction of moving ice masses in the coastal belt of the ocean, to clarify the possible breaks and declinations as to the general drift pattern and thus arrive at conclusions of navigational character.

Despite the fact that the materials of direct observations on currents in the Arctic Ocean have not yet been processed and we have to use the data of currents arrived at by indirect computations, the problem on the processing of prognosis of ice drifts in high latitudes can be faced even with the existing means at hand. The presence in the ocean of a few stations that carry out continuous observations on wind elements, on air pressure and ice drift permits the preparation of comparatively dependable charts on the baric relief and drift computations covering the entire ocean.

The role of high latitudinal processes in the formation of ice conditions on the Northern Sea Route is so great, the range of their phenomena so significant that the effects must always be taken into consideration when preparing forecasts of navigational conditions on the Northern Sea Route.

The Scientific Research Station NP-4

(The Arctic Ocean)

September-October 1955